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MEASURING STRUCTURAL FLEXURE TO IMPROVE PRECISION TRACKING

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Abstract

Ship flexure is currently an uncompensated phenomenon that is accounted for in system error budgets without apparent compromise of system performance. However, upcoming system performance requirements may not be able to absorb ship flexure errors. Analyses have been performed throughout the AEGIS development program to determine the magnitude of ship flexure which predicted several milliradians of flexure between arrays under temperature loading, but analysis should be validated by test and measurement. Flexure has been measured in other ship classes; however, none of these results can be directly applied to AEGIS.

We describe ways of conducting a test to effectively measure the magnitude of ship flexure using current technology and validate predictive models. A secondary goal of measurements would be to allow us to evaluate these new technology systems for possible use in measuring static and dynamic flexure for compensation during tactical combat system operation and thereby improve the accuracy of intercepts and other engagements.

Introduction

The purpose of this presentation is to provide information on an effort to determine realistic values for ship flexure based on test measurements of a ship dockside and at sea. This would be the first step in a long evolutionary process to determine error budget implications for future systems, including Exo-Atmospheric Intercepts of Tactical Ballistic Missile Defense (TBMD), and how we are going to get there.

Current alignment methodology has been adequate for state of the art sensor and weapon systems currently available.[1] However, the ability to maintain alignment under operational conditions may have to improve to meet the requirements of near future advanced weapons and sensors.[2,3] To compensate for biases not precisely known at present, new applications of improved technologies may have to come into use to support these weapons. These are concepts that up until now have been neglected in the design and integration of ship systems.

Background

The combat system elements are typically aligned at night, when temperature effects are stable, and the ship is dockside with no appreciable sea effects. This would represent a null flexure state.

Currently, ship flexure is an uncompensated phenomenon that is accounted for in system error budgets without apparent compromise of system performance.[1] Upcoming system performance requirements may not be able to absorb ship flexure errors or other system errors and biases that have been tolerated up to this point.

It is important to understand how error budgets work, of which flexure is one parameter. Error budgets are usually used to determine system operation capability during the most extreme conditions, such as high speed maneuvers or high sea states. The magnitude of flexure usually decreases very quickly when the actual combat system conditions are more sublime. Consequently, the maximum estimated values will only occur a small percentage of time. In order to compensate for ship flexure, we have to worry about static and dynamic conditions and the parameters that need to be controlled.

Flexure is usually segmented into dynamic and static categories, the difference being the time characteristics. Dynamic flexure produces a random, continuously changing error, while static flexure is more like a bias, as it remains constant during a typical combat system engagement. Dynamic flexure is composed of errors due to ship motion from waves and maneuvers, and vibration due to a variety of sources. The major static flexure contributor is temperature,

with secondary effects caused by ship loadout changes and steady winds.

Ship flexure manifests itself as uncompensated relative angular differences between different shipboard elements from the compensated aligned state. Originally, flexure estimates were based on measurements from previous ship classes and cursory analyses. The accuracy of those measurements and the rigor of the tests were not good enough to base the lives of millions of people on. The analyses were not benchmarked against sufficient measured data to validate any models.

Because of this, our current system error budget utilized large estimates of flexure. Even with very conservative estimates we managed to reach an acceptable error budget for performance because our closed loop tracking is very tight and our illuminator beam width is very large.

However, upcoming system performance requirements may not be able to absorb ship flexure errors. The system will not be able to utilize an illuminator and the optical viewing cone will be small. In addition, the target will have a small optical crosssection and will be moving fast. The TBMD Exo-Atmospheric tests are designed to not excessively stress the system. One of the conditions to reduce stress is to maintain the target and the interceptor on a single array. Ship flexure may create array to array target hand-over problems during exo-atmospheric TBMD intercepts and under certain tactical conditions may possibly produce unacceptable performance.

To maintain "perfect" alignment during operation, it would be necessary to incorporate an active compensation system. Such a system has not been necessary for successful core AEGIS operation. It also has not been demonstrated.

Exo-Atmospheric Intercept

An intercept volume is the space a target and a Kinetic Weapon might fill during the same short, extended time period. A physical intercept volume is dependent on physical cross sections and the time window in which those cross-sections might be in contact. Intercept timing is dependent on the angle of attack. A nose on intercept will give a longer time window, but a perpendicular angle of attack will give an extremely small time overlap (Figure 1).

The angle of attack, or aspect angle, is dependent on deployment and tactical timing. Let's play Tom Clancy for a while here and produce a fictional scenario where hostile actions are determined to be imminent from North Korea (Figure 2). An AEGIS hull leaves Sasebo, Japan and deploys to protect a staging area for naval task forces. A missile is launched from North Korea towards the Tokyo area. The intercept point could be at right angles, the smallest intercept volume, and it could have the target on one array and the interceptor on another array. The dramatic impact should be high.

The simple geometry of our intercept can be estimated by dividing one axis of the cross section by the range. As a representative situation for illustration purposes, assume a 1 yard dimension for crosssection/arc-length and a range of 500 nautical miles (1000 kilo-yards). This would require an angular intercept solution of 1 micro-radian. If ±1000 yards is allowed for error budget contribution and an optical tracker completes the intercept solution, the current alignment verification (AV) tolerance at array normal results. This AV tolerance is applied dockside at night and is relative between an array and the forward Illuminator, it is not relative to true. Given the errors of the systems involved, statistical filtering would still have to be very good.

The accuracy considerations for other advanced weapons and sensors can be just as strenuous, if not more so. If a directed energy weapon were utilized, its pinpoint targeting requirements could also be on the order of 1 micro-radian.

Given two or more planar arrays, the relative flexure between them will be important. Relative flexure measurement problems between arrays is compounded by having them mounted in more than one deckhouse (CG 47 Class) (Figure 3). This leads to another flexure issue, hull flexure between sensors and launchers/guns. The longer a hull and the more dispersed the elements, the more displacement flexure will cause.

The additional error Array to Array flexure contributes to an Error Budget is almost double that of a Single Array solution. We are very sensitive to Array to Array flexure. We also have to keep in mind that the smaller our errors, the more maneuvering fuel that will be available for final intercept.

Previous Flexure Measurements

Flexure has been measured in other ship classes; however, none of these results can be directly applied to AEGIS. In 1972, static flexure measurements were made on the USS Stein (DE-1065)[4] over a 24 hour period. It was a 24 hour test where the minimum temperature was 58° F and the maximum temperature was 90° F. The maximum change in rollerpath

inclination was 0.9 milliradian (mrad) between the director and the gyro. The indications from the documentation are that these measurements were not used to validate a structural model.

Also in 1972, dynamic flexure measurements were made on USS Horne (DLG-30).[5] Between the aft end of the missile director equipment deck and the aft end of the helo deck there was a 1.2 mrad excursion horizontally and 2.4 mrad excursion vertically in Sea State 3. These measurements suggest a TBMD problem might be extrapolated for Sea State 5 conditions (a factor of 3.6). What impressed an observer, now the AEGIS Alignment In-Service Engineering Agent, was the 1 mrad excursions horizontally and vertically witnessed while the ship went through small swells.

In 1978, dynamic flexure measurements on the USS Elliott (DD 967),[6] a similar hull to AEGIS Class Cruisers, suggests a problem may exist even in calm seas and slow turns - 3.5 mrad excursions in roll typical, with a worst case amplitude of 7.0 mrad. There is even a worst case event during high speed maneuvers - 12.3 mrad in roll and 22.0 mrad in pitch. That is almost an order of magnitude higher than the static value used in the Exo-Atmospheric Intercept Error Budget. If these values can be believed as true, then the project has a problem that would have to be compensated. However, none of these results can be directly applied to AEGIS. The measurements used old technology and the tests were not rigorous. Millions of lives may be at stake, we should not rely on these old measurements.

What It Would Take To Measure Flexure Now

We have identified ways of conducting a test to effectively measure the magnitude of ship flexure using current technology. A secondary goal would be to use this test to evaluate new technology systems for possible use in static and dynamic flexure measurement for compensation during tactical combat system operation.

The results of ship static flexure measurements can be used to determine if significant flexure occurs and if we should continue on with this effort with at sea measurements of dynamic flexure. The results of the flexure study can be used to validate the accuracy of analyses and their associated structural models.

Objectives

This test will:

- Measure ship static flexure states that can be used to extrapolate to extreme combat conditions
- Show how it impacts error budgets for advanced weapons integration and if subsequent at sea measurements of dynamic flexure should be performed.
- Validate the accuracy of previous static analyses and their associated structural models.
- Provide experience with laser system technologies to determine their capabilities and future usefulness for measuring dynamic flexure for Real-Time tactical compensation.
- Utilize lessons learned from measurement of ship static flexure and perform measurements of ship dynamic flexure.
- Develop and validate structural models capable of simulating CG 47 and DDG 51 Class ships in dynamic operational conditions. The lessons learned from this validation effort might be utilized in developing future ship classes, such as SC-21 classes.

Technology

Where previous flexure tests concentrated on either laser systems, gyro systems or accelerometers, we now are merging different complementary technologies to overcome weaknesses of each individual technology.

We plan to use two optical systems, SMX (SpatialMetriX Corp.)[7] automatic laser tracker system (Figure 4) and DRS Photronics, Inc.[8] Triaxial Measurement System (TMS) (Figure 5), to run a test to measure static (temperature loading) flexure on a ship at a shipyard over a period of a few weeks during sun/shade daytime/nighttime temperature changes. The SMX system measures array to array flexure point to point in Cartesian Space and the DRS system measures hull flexure as an angular change. We can then merge the two distinct methods to give a measured estimate of the ship's static flexural condition.

Ring Laser Gyros (RLG) have been in service for about twenty years, including military and commercial applications. They are attractive for dynamic flexure measurement because they are proven in dynamic environments to give real-time, accurate and reliable data in a small (as small as fist size) package. Fiber Optic Gyros (FOG) will also be considered.

Photogrammetry will periodically be used to validate static flexure measurements and link independent systems.

Temperature gauges would be used to measure ambient and structural temperatures for correlation between test periods and with analyses. We have participation from AEPTEC Microsystems, Inc.[9] and the National Institute of Standards and Technology (NIST), which will allow a large number of temperature sensors to be automatically sampled, stored and viewed by computer with a minimum of cabling by using wireless technology.

The SMX laser tracker system provides 3D angular measurements of multiple targets. The advantage of SMX is that it is an existing technology with existing computer software, already being used for measurements of static flexure in a single space at distances of about 100 feet and can be easily automated to take and record measurements over time. The disadvantages are that SMX requires a clear line-of-sight between the laser and targets, the laser is fragile (however, a hardened target is available) and the measurement updates are relatively far apart (on the order of seconds, not milliseconds) to measure dynamic flexure. The most practical location for this piece of equipment is in the AN/SPY-1 deckhouse.

Another optical system, the DRS TMS, is similar in capabilities and drawbacks to SMX. It has been successfully used in the accurate alignment of navigation systems and weapons on the F-22 fighter and AH-64D helicopter programs. As an added consequence, the TMS is already militarized. An advantage of TMS is that it can refresh its output continuously, so it can be used to measure dynamic flexure. A disadvantage of TMS is that it currently uses a target that is limited to about two inches in allowable displacement, which limits the distances over which flexure can be measured. The most practical use of this equipment is to measure hull deflections.

The ship's navigation system on the AEGIS ships are being retrofitted from the gimbaled WSN-5 to RLG WSN-7 primarily to take advantage of their advantages of accuracy, and increased reliability and consequent reduced downtime. We will be using small RLGs to reduce room arrangement problems. They do not require Line of Sight to operate. Their weakness is during periods when the ship is more motion stable and the systems develop large biases.

By combining these laser systems with Ring Laser Gyros we can cancel out the weaknesses of these systems with the strengths of the other systems.

We will perform the tests in an interactive environment that will allow us to correct problems as they occur and allow us to simulate an active flexure compensation system.

The product should be a tactical flexure compensation system that will allow a ship to fire their ordnance at any time with high accuracy and excellent probability of kill.

Test Execution

For static flexure measurements, we are concerned most with temperature differentials produced by solar heating. The best locations to conduct testing will have large differentials between night and day time temperatures with long periods of direct sun. We are also looking for a location that has both AEGIS ship classes available. Mayport is one candidate location, where temperature gradients are quite large in the fall and spring.

Once measurements are taken, we need to compare them to hull structural finite element model results with the same parameters. The models may have to be rectified to make the match better. The models are fairly complex with thousands of elements (Figure 6). Once the models are refined and acceptable, the models can be used to extrapolate to extreme combat environments, both hotter and colder. With those results we can evaluate the need to compensate for flexure for TBMD or other advanced systems.

With static flexure measurements in hand and some of the comparisons to models completed, the need to continue on with dynamic flexure measurements can be evaluated. If a go ahead is given, we could incorporate the lessons learned during static flexure measurements to the at-sea measurement effort. We will perform the test at-sea in a way to prototype a tactical flexure compensation system. Cruisers will be taken through a series of high speed turns, allowed to roll, taken through full reverses, and taken through swells in order to accumulate data. Modifications may be necessary to a DDG deckhouse to provide Line-of-Sight (LOS) for a laser system, so destroyers may not be used during these test measurements because of the modifications that would be necessary to take measurements.

The same type of comparisons will be performed with the dynamic data once it is compiled. Dynamic modeling is different than static modeling and not

much has been done in this area, so creative methods will probably have to be employed to provide consistently matching comparisons to high speed turns, rolls, interactions to swells and other physical conditions.

Once the models and techniques are verified, we can extrapolate to extremes in the combat environments and further evaluate the need to provide any flexure compensation.

Conclusion

Ship flexure may be a problem that TBMD and other advanced weapon systems have to compensate for. Previous studies have produced results which indicate that flexure magnitudes have been large, but we are unable to apply these results directly to our current AEGIS Class hulls. Therefore, we need to develop a test and evaluation effort to measure flexure, produce validated models and determine if flexure will be a problem in obtaining the necessary accuracy for TBMD and other upcoming systems. Part of that evaluation will determine if a real time flexure compensation system is necessary, but we will also proof out existing technology for a potential compensation system.

In the meantime, new ship classes should make design allowances for measuring and compensating for ship flexure.

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Biographies

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Dr. Day has been working Combat System Performance issues with Naval Systems at Lockheed Martin - Government Electronic Systems since 1985. He received his Ph.D. in Physics from the University of Kansas in 1983 and has B.S. degrees in Mathematics and in Physics from the University of Wisconsin - Eau Claire. Previous to college, he served in the U. S. Army - Corps of Engineers (Topographic), schooled at Fort Belvoir with duty at Yuma Proving Grounds and in Korea.

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Mr. Arruda is currently Branch Head of the AEGIS Combat System Ship Integration Branch in the Technical Division of PEO-TSC. Under this position, John is also responsible for EMI/EMX and the Combat System Shock program. The ship integration branch is also responsible for Combat System Support Equipment, Ship Alteration Integration, Combat System Baseline installations, and TBMD Ship Integration.

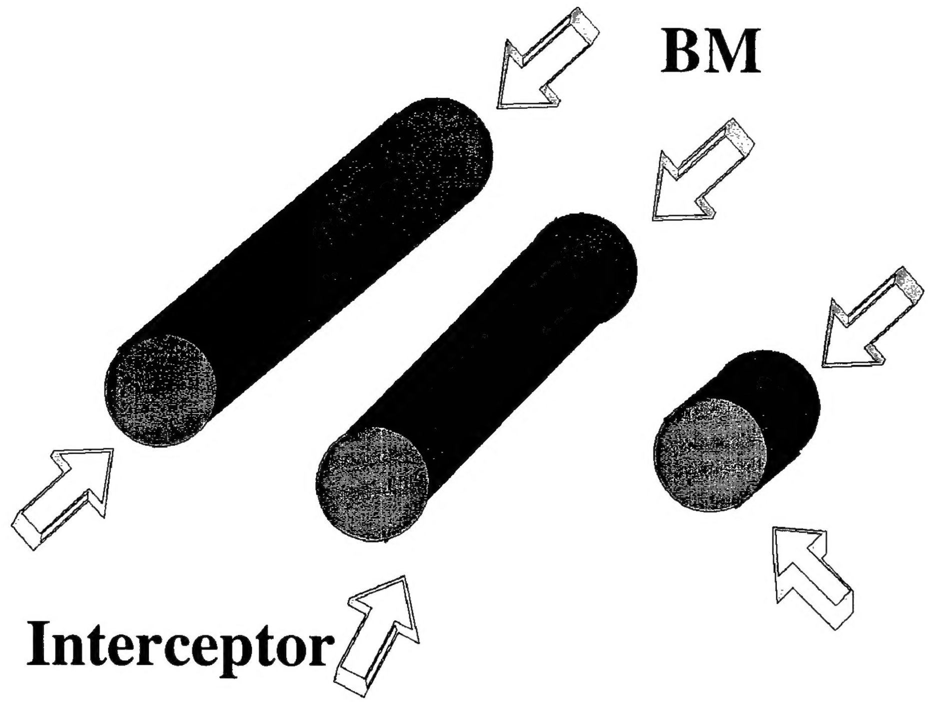

Figure 1. Intercept Aspect Angles can effect the size of the Intercept Volume.

Figure 2. Fictional Scenario of an Exo-Atmospheric Intercept

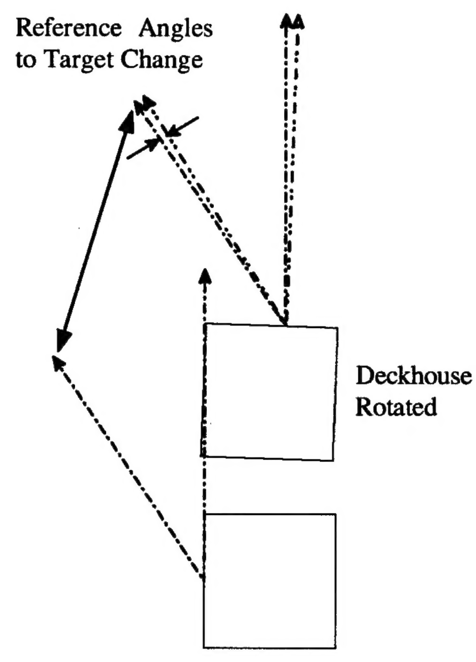

Figure 3. Arrays on Two Deckhouses can have Different Angles to a Target because of Ship Flexure

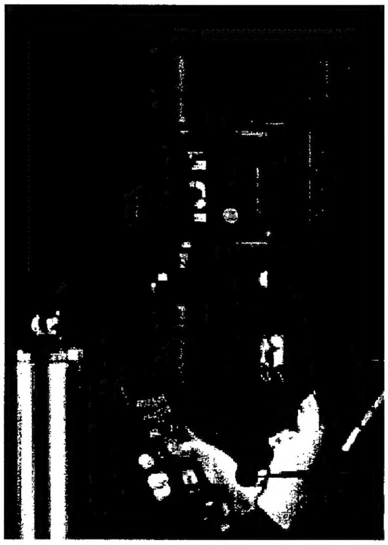

Figure 4. SMX Auto-Tracking Laser.

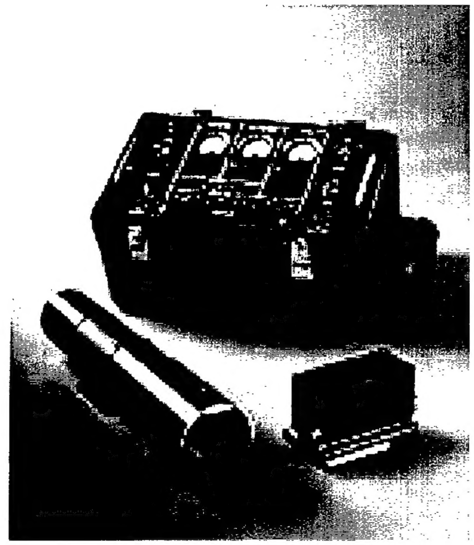

Figure 5. DRS Photronics Triaxial Laser

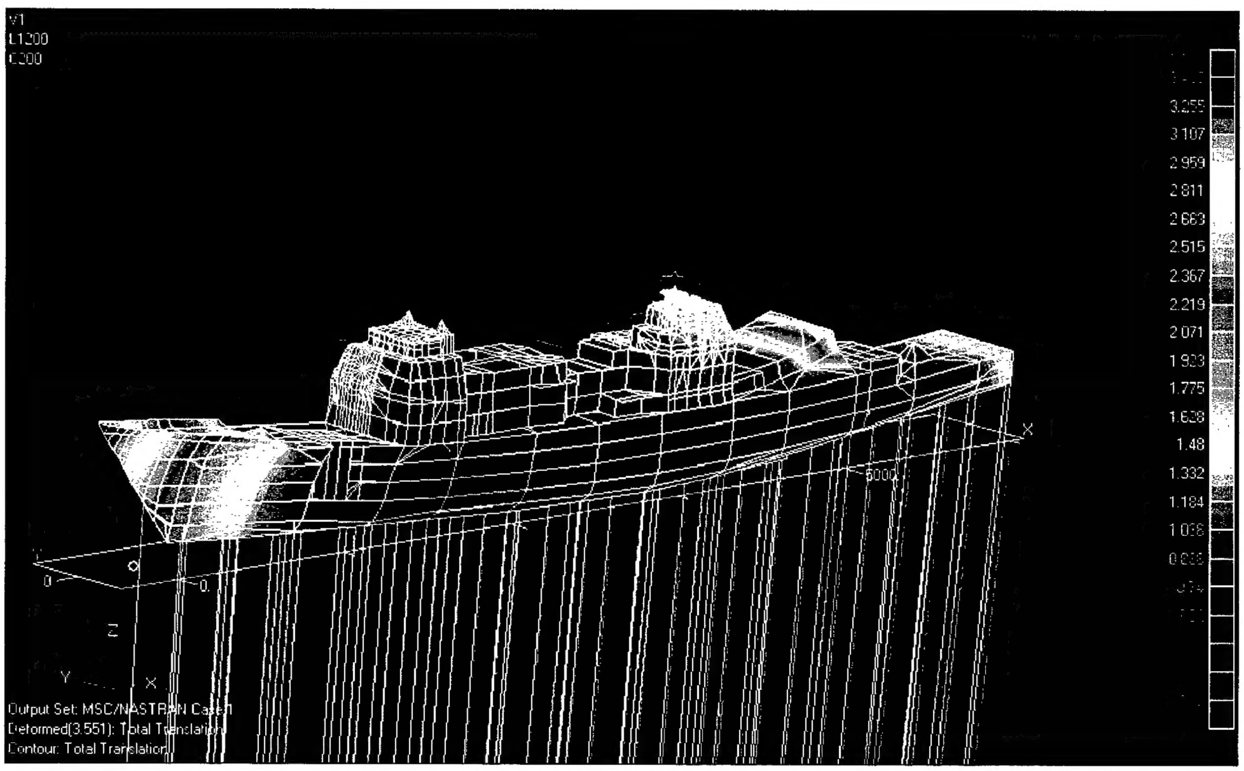

Figure 6. AEGIS Cruiser Finite Element Model

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